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HYDROMECHANICS

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MATERIALS SURVEY FOR THE RESCUE AND SEARCH VEHICLES OF THE DEEP-SUBMERGENCE SYSTEMS PROJECT

by

A. R. Willner and M. L. Salive

STRUCTURAL MECHANICS LABORATORY
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ABSTRACT

Factors influencing the selection of materials for the pressure hulls of vehicles for the Deep Submergence Systems Project are presented. Aluminum, steels, and titanium are discussed with respect to such properties as chemistry, strength, fatigue, toughness, and corrosion. The suitability of these materials from a fabrication standpoint is also explored. It is concluded that 721-titanium alloy appears to be the best candidate for the pressure hulls of deep-submergence vehicles where high-strength low-weight characteristics are required.

ADMINISTRATIVE INFORMATION

By Special Projects Office, Department of the Navy, Project Order 5-0003 of 3 December 1964, the David Taylor Model Basin was given the assignment to develop and provide structural design information, including material and fabrication analysis, for the pressure hulls of vehicles developed under the Deep-Submergence Systems Project.

This report presents the material and fabrication analysis for metallic pressure hulls. Structural design information on the tradeoffs between pressure hull materials, configurations, and buoyancy is presented in Taylor Model Basin Report 1985.

INTRODUCTION

The Deep-Submergence Systems Review Group (DSSRG) was established in April 1963 to (1) review the Navy's plans for the development and procurement of components and systems related to location, identification, rescue from, and recovery of deep-submerged large objects from the ocean floor, (2) recommend changes to such plans which will result in expeditously obtaining sufficient capabilities which could be used to recover large objects from the ocean, (3) develop a 5-year program for implementing recommendations, and (4) recommend means and organization of responsibilities for implementation.

In February 1964 the Group reported its findings and recommendations. After review of the report, the Secretary of the Navy assigned the responsibility for implementation of the program, which was renamed the Deep-Submergence Systems Project (DSSP), to the Navy's Special Projects Office.

Two primary objectives of the DSSP are to develop the capability of rescuing personnel from distressed submarines and to locate and recover small objects from the ocean depths. Two distinct vehicles, the Rescue Vehicle and the Search Vehicle, will be developed to achieve these objectives. Present plans are to have six rescue vehicles and four search vehicles operational by 1970.

Because of weight limitations, materials presently used for the pressure hulls of submarines will not be suitable for the pressure hulls of these vehicles. A variety of metals with improved strength-to-weight ratios are currently available or under development. This report evaluates the most promising of these materials and provides background information to support the selection of the materials considered to be most suitable.

FACTORS INFLUENCING MATERIAL SELECTION

All materials contain exogenous and indigenous defects. It can be expected that with the proper orientation of these defects some tensile stresses may develop at the tips of a defect due to Poisson's effect. However, the tensile stresses developed will be smaller than the applied compressive stresses. Consideration will have to be given to the magnitude of the residual tensile stresses that may be present due to fabrication or to metallurgical transformation products. The operating compressive stress may be below the yield strength but above the material's compressive elastic limit. Therefore, in unloading, a material will experience a slight Bauschinger effect or have a small residual tensile stress. The major loading of a submersible is compressive; if not stress relieved, the material will experience an alternating stress cycle due to the presence of residual tensile stresses. In addition, the material integrity problem will be further aggravated by the presence of properly oriented defects which may develop tensile stresses at the acuity of the defect. Therefore, it is necessary to have a material which will not propagate a catastrophic crack if these defects grow to a size that may be considered critical. To ensure that the material selected can meet design requirements for the pressure hull of the rescue and search vehicles, the following factors should be considered:

1. Ability of baseplate and weldment to withstand cyclic loading in sea water before initiating a fatigue crack.
2. Ability of baseplate and weldment to withstand crack propagation.
3. Resistance to stress corrosion.
4. Resistance to general corrosion.

The above factors as well as others involving fabricability and mechanical properties, are discussed more fully in the following sections.

The materials and thicknesses being considered for the pressure hulls of the search and rescue vehicles are as follows:

Material	Compressive Yield Strength (ksi)	Nominal Shell Thickness (in.)	
		Search	Rescue
Steel	100	———	1 1/16-1 1/4
↓	140	———	1-1 1/2
↓	150	2-2 1/2	15/16-1 1/4
↓	160	———	7/8- 1 1/8
↓	180	2-2 1/2	7/8-1 1/8
Steel	200	1 7/8-2 1/4	———
Titanium	110	3-3 1/4	1 1/4- 1 1/2
↓	150	2 1/2-2 3/4	1-1 1/2
Titanium	180	2 1/8-2 1/4	———
Aluminum	35	———	2 1/2-3
Aluminum	60	5 1/4-5 1/2	1 3/4-2
Glass Reinforced Plastic	50	———	~2
↓	60	5 3/4	———
↓	75	4 1/2	———
Glass Reinforced Plastic	100	~3	———
Glass	~150	~2 1/4	1 1/4
Alumina	~300	~1 1/4	3/4

The Navy has made an extensive evaluation of the various materials available for use in deep-ocean vehicles and fixed-bottom installations. The individual reports on each material and its associated fabrication problems have been prepared and are published in a single volume.[1] Information from this report and the latest data that are presently available are reviewed and discussed herein as potential materials for metallic pressure hulls of the rescue and search vehicles.

It should be understood that there are a number of metals or nonmetals that can meet one or more specific sets of conditions; however, most of the available information is based on laboratory tests without any correlation to actual service performance. Therefore, one of the prime considerations in selecting a material is to determine whether or not the available information can be used to ensure reproducibility of specified minimum properties regardless of whether they be mechanical, physical, or chemical.

MATERIALS UNDER CONSIDERATION

The materials discussed herein are titanium, steel, and aluminum. Glass and fiberglass-reinforced plastics have been discussed in detail in the Project SEABED report[1] and are also discussed in the report dealing with the design analysis for DSSP vehicles.[51]

Each material will be discussed in terms of its chemical composition, mechanical properties, fatigue, notch toughness, resistance to corrosion, and production requirements.

CHEMISTRY

Chemical composition ranges are given in Table 1, not for the purpose of procurement but mainly to show that there are a number of steel, titanium, and aluminum alloys available to meet a specific property. In some cases, the chemical composition ranges for the commercially available materials are well established; e.g., the Navy's HY-100 steel and the lower strength aluminum alloys. However, the specific ranges given for the

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[1] References are listed on page 37.

TABLE 1

Chemical Composition Range of Materials Considered for DSSP Vehicles

Steels

	Chemical Composition, Percent[1]													L_{s-95}
Material	C	Mn	P	S	Si		Ni	Cr	Co	Mo	V	Ti	Aℓ	Cb	in.
HY-100	0.20	0.10/0.40	0.025[2]	0.025[2]	0.15/0.35		2.25/3.50	1.00/1.80	—	0.20/0.60	0.03	0.02	0.25 Cu	—	0.6/6.8
HY-140	0.09/0.13	0.60/0.90	0.015	0.015	0.20/0.35		4.6 /5.3	0.45/0.65	—	0.47/0.62	0.04/0.09	—	—	—	4/10
HP-140	0.20/0.25	0.10/0.15	0.01	0.01	0.10		2.75/3.25	1.4 /1.65	—	0.80/1.00	—	—	—	0.03/0.07	2/5
7220	0.08/0.12	0.10/0.15	0.01	0.01	0.10		6.5 /7.5	0.10/0.35	1.75/2.25	0.10/0.35	0.15	—	—	—	—
HY-180	0.03	0.10	0.01	0.01	0.10		11.5/12.5	4.75/5.25	—	2.75/3.25	—	0.10/0.25	0.15/ .30	—	—
HY-190	0.03	0.10	0.01	0.01	0.10		11.5/12.5	4.75/5.25	—	2.75/3.25	—	0.18/0.33	0.20/0.35	—	—
9425	0.23/0.27	0.10/0.15	0.01	0.01	0.10		6.0/ 9.0	0.10/0.35	3.5 /4.0	0.10/0.35	0.15	—	—	—	—

Titanium

Material	Aℓ	Cb	Ta	V	Cr	Mo	Sn	Mn	C	N_2	O_2	H_2	Fe	Cu	Other
HY-110	6.0/7.3	2.0/2.75	0.6/1.2	—	—	—	—	0.01	0.03	0.012	0.09	0.008	0.18	—	0.25
HY-150	5.0/6.0	—	—	5.0/ 6.0	—	—	1.5/2.5	—	0.08	0.012	0.38	0.005	0.5/0.9	0.5/0.9	0.25
HY-150	5.5/6.5	—	—	3.5/ 4.5	—	—	—	—	0.08	0.012	0.13	0.005	0.25	—	0.5
HY-140	2.5/3.5	—	—	12.5/14.5	10.0/11.0	—	—	—	0.08	0.012	—	0.010	—	—	0.5
HY-130	6.5/7.5	—	—	—	—	3.5/4.5	—	—	0.08	0.012	—	0.010	0.25	—	—

Commercially Available Aluminum Alloys Considered for DSSP Submersibles

Material	Commercial Designation
HY-30	6061-T6
HY-40/50	7002
HY-40/50	7039
HY-40/50	7106
HY-60	7079-T6

1. Maximum unless a range is indicated.
2. Combined P plus S to be less than 0.045 percent.

higher strength steel, titanium, and aluminum alloys are only nominal since they can be considered to be still under development even though some of them are commercially available. In general, the exact chemistry range for making a given mill product is considered to be the producer's proprietary information; an alloy composition made to fall within a specified range does not necessarily meet all the properties specified. The producer varies the alloying elements singly or in combinations to meet a given set of conditions. Thus, chemistry plays a very important part, especially for the higher strength materials, when meeting a given set of conditions. Information regarding the effects of a specific alloy addition on the properties of the materials given in Table 1 is available in References 2, 3, and 4.

MECHANICAL PROPERTIES

One of the most important material properties in designing the pressure hull, is the compressive yield strength. Other conditions that have to be satisfied are tensile, fatigue, and notch toughness properties as well as corrosion resistance and fabricability. Table 2 compares the nominal mechanical properties that can be expected for the designated alloys in the required hull thicknesses. It should not be implied that because of the compressive yield strength shown for the various alloys these materials are suitable for meeting all design requirements.

Compressive stress-strain curves obtained by the Model Basin for each of the materials given in Table 2 are depicted in Figures 1 through 7. With each compressive stress-strain curve in these figures, the various ratios of elastic, tangent, and secant modulus are plotted as a function of compressive stress. It should be understood that these are not normalized stress-strain curves plotted to the minimum yield strength but are actual stress-strain curves of material. However, the shape of the stress-strain curves is representative for each given material and can be used for design purposes.

The tensile true stress-true strain curves for the various materials are given in Figures 8 through 14. The true stress-true strain curve for 7079-T6 aluminum (Figure 14) is typical of all high strength aluminum alloys. It should be noted that the slopes of the curves, which are

(text is continued on page 22)

TABLE 2

Nominal Mechanical Properties Reported for Materials Considered for DSSP Vehicles

Material	Grade	Commercial Designation	Compressive Yield Strength ksi	Tensile Yield Strength ksi	Ultimate Tensile Strength ksi	Elongation in 2 in. percent	Reduction in area percent	Transverse Cv - 32 F ft-lb	Vehicle	References
Steel	HY-100	HY-100	110	105	125	21	65	70	Rescue	DTMB Data*
	HY-140	HY-130/150	154	145	161	19	63	45	Rescue	DTMB Data*
	HY-140	HP-140	168	158	175	20	69	92	Both	DTMB Data*
	HY-1	7210	---	164	175	16	57	50	Both	Republic Steel*
	HY-180	12% Ni Maraging	---	160**	---	--	—	≥50**	Rescue	**
Steel	HY-180	12 Ni Maraging	196	187	190	14	56	42	Both	DTMB's Data*
		4335	214	192	212	15	49	34	Both	DTMB's Data*
Titanium	HY-110	721	110	105	120	10	20	35	Both	DTMB's Data
	HY-140	662	---	140	150	8	20	15	Both	RMI & TMCA
	HY-140	6 Al-4 V	---	140	150	8	20	17	Rescue	
	HY-130	6 Al-4 V	---	125	130	6	15	17	Search	
	HY-160	13 V-11 Cr-3 Al	---	170	180	4	-	--	Search	
Titanium	HY-140	7 Al-4 Mo	---	140	150	8	20	17	Search	
Aluminum	HY-30	6061-T6	36	35	42	10	—	--	Rescue	MIL-HDBK-5
	HY-40/50	7002	---	52	61	14	—	—	Rescue	Producer (Reynolds)
	HY-40/50	7039	69	55	65	13	—	—	Rescue	Producer (Kaiser)
	HY-40/50	7106	---	50	55	6	—	—	Rescue	Producer (Alcoa)
	HY-60	7075-T6	64	62	72	6	—	—	Rescue	Producer (Alcoa)
Aluminum	HY-60	7079-T6	69	56	66	4	—	—	Search	Producer (Alcoa)

*Unpublished data

**Estimated minimum, steel still under development

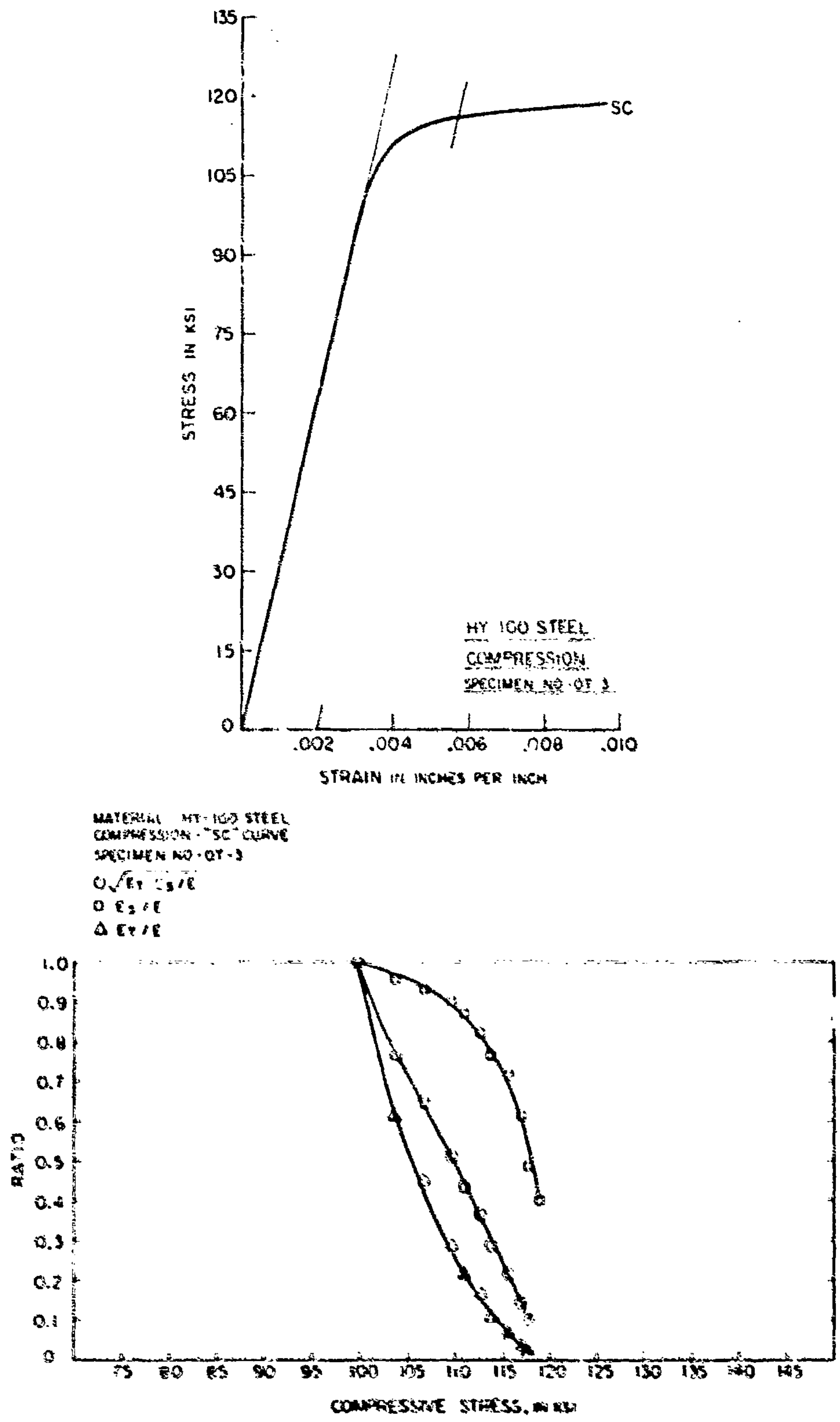

Figure 1 - Compressive Stress-Strain Curve and Plots of the Ratios of Tangent and Secant Moduli to Young's Modulus as a Function of Compressive Stress for HY-100 Steel

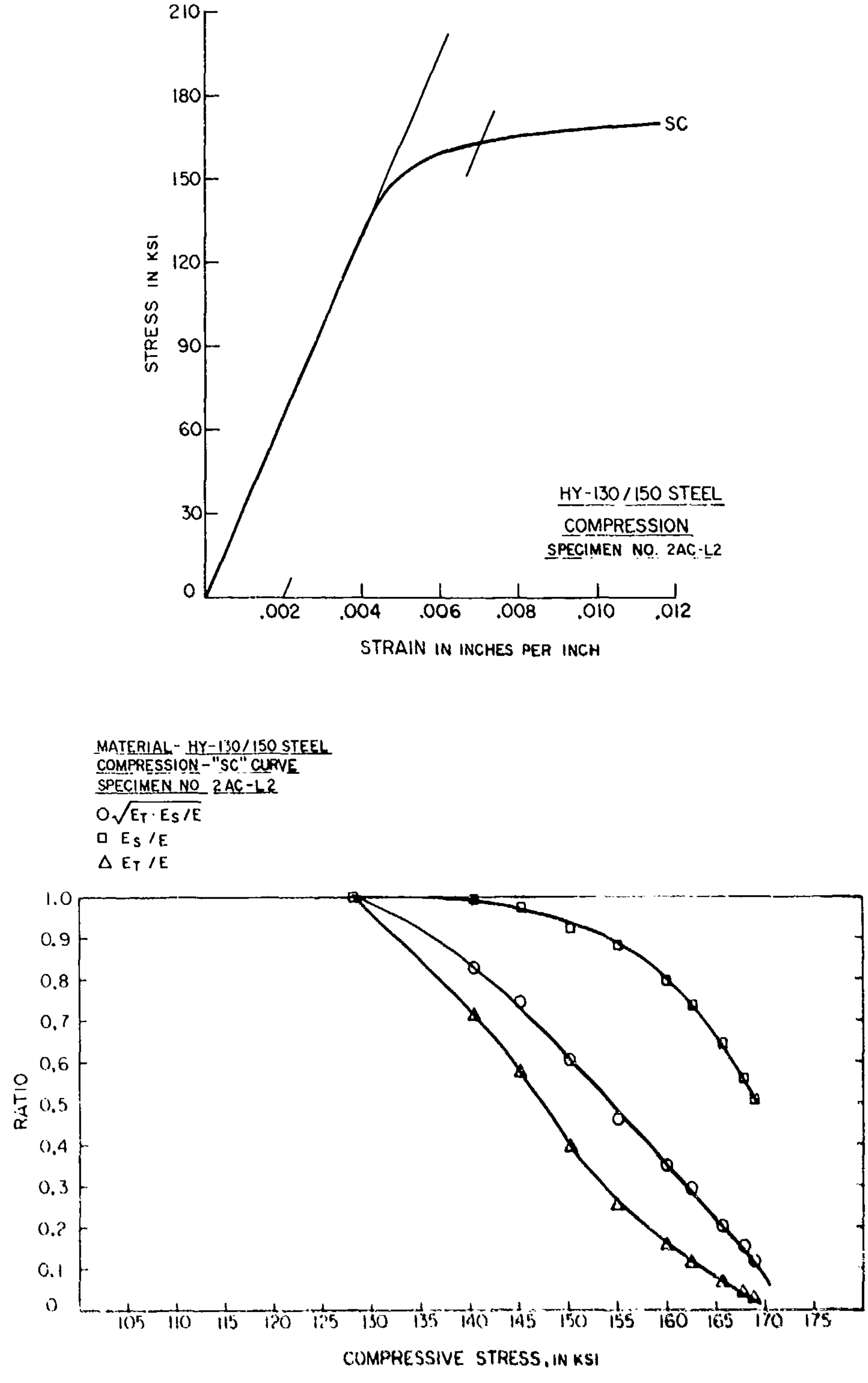

Figure 2 - Compressive Stress-Strain Curve and Plots of the Ratios of Tangent and Secant Moduli to Young's Modulus as a Function of Compressive Stress for HY-130/150 Steel

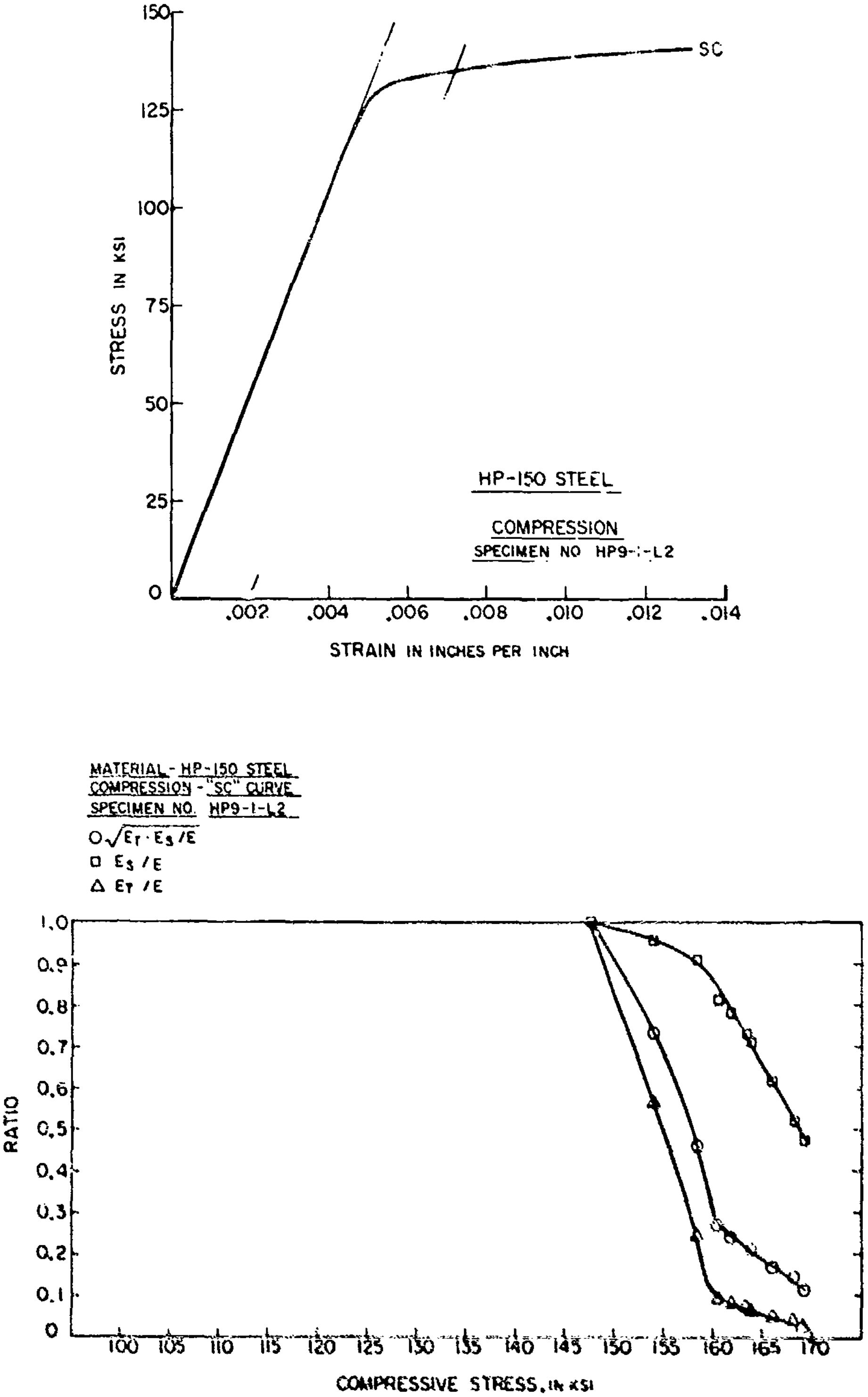

Figure 3 - Compressive Stress-Strain Curve and Plots of the Ratios of Tangent and Secant Moduli to Young's Modulus as a Function of Compressive Stress for HP-150 Steel

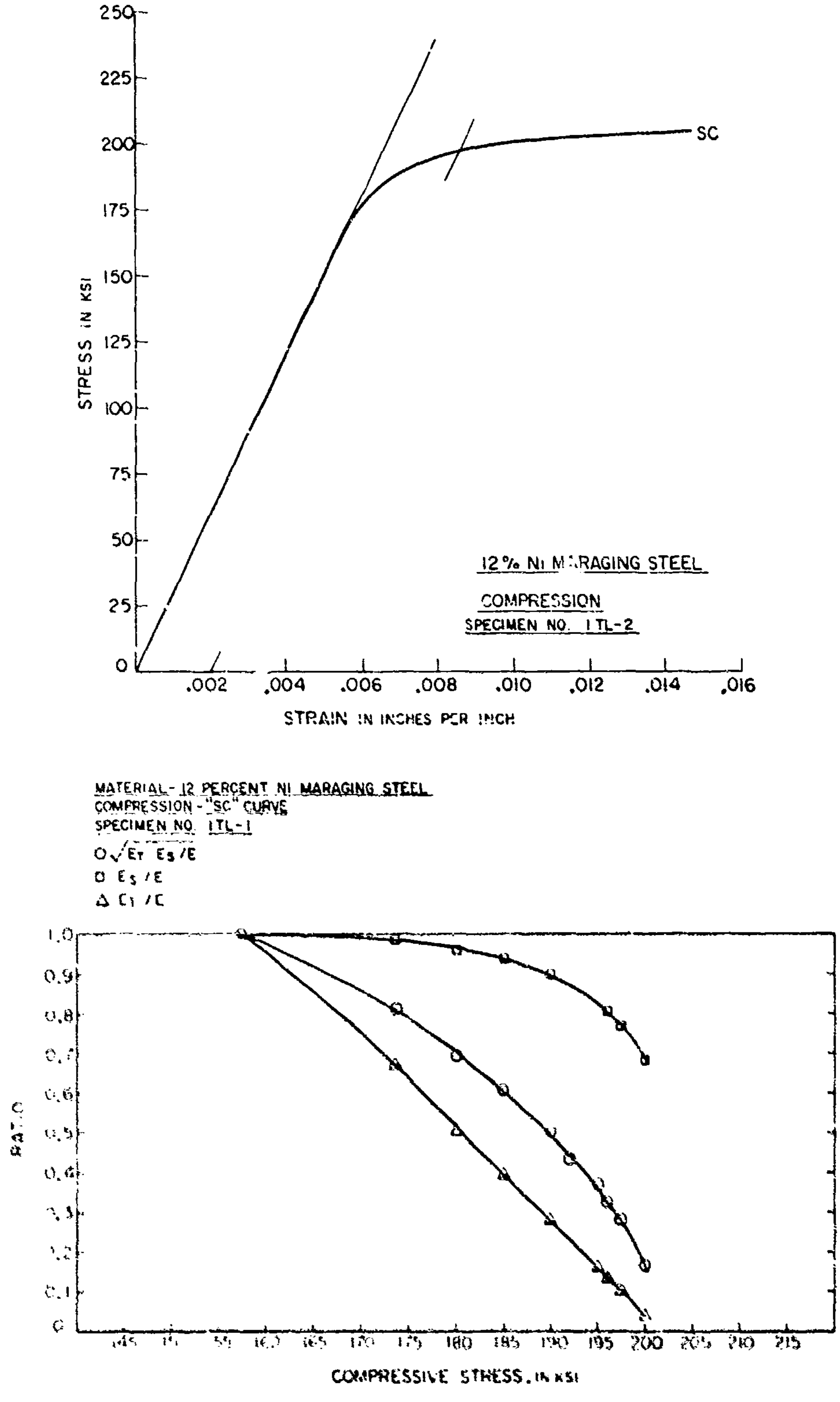

Figure 4 - Compressive Stress-Strain Curve and Plots of the Ratios of Tangent and Secant Moduli to Young's Modulus as a Function of Compressive Stress for 12 Percent Nickel Maraging Steel

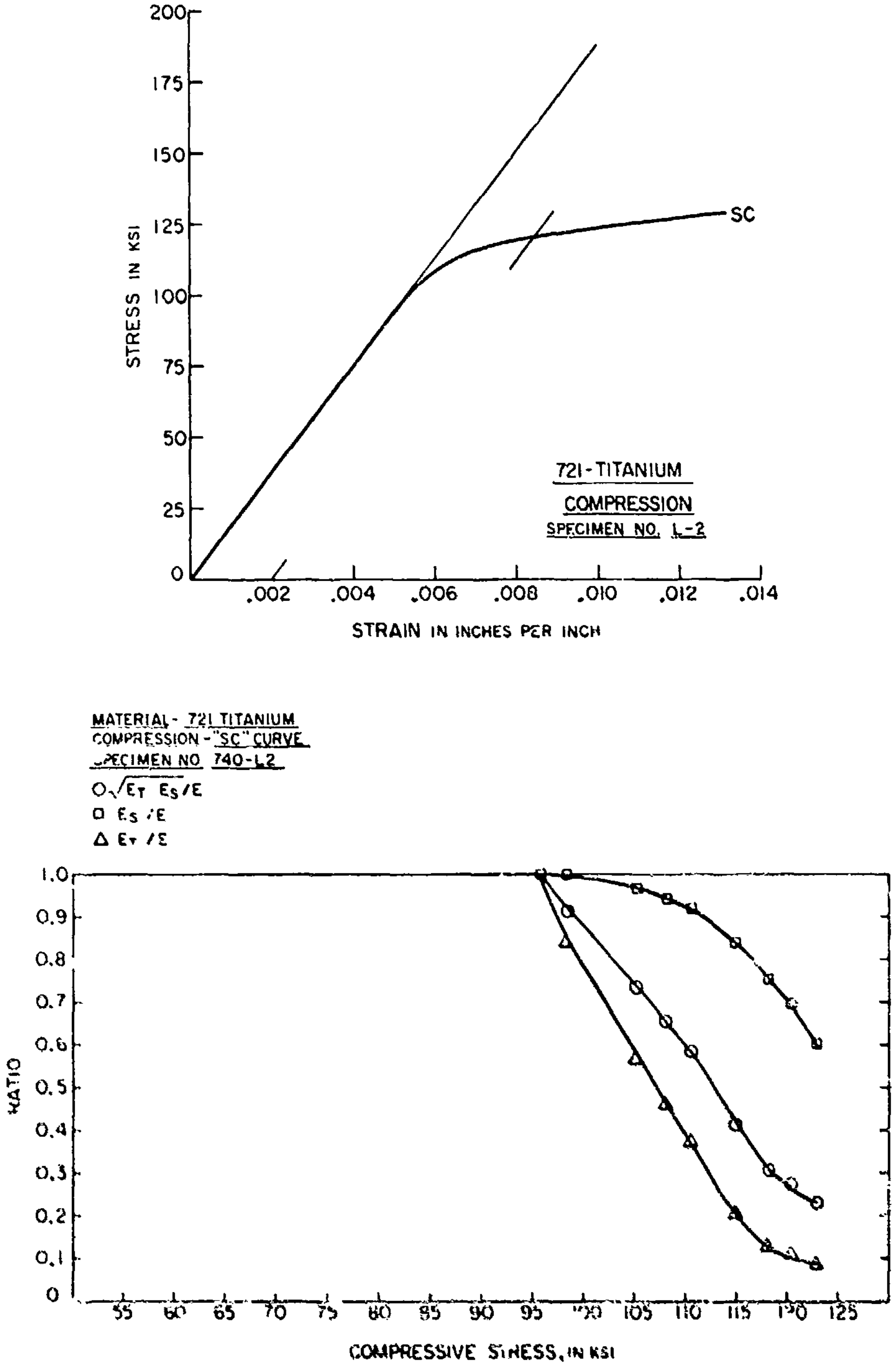

Figure 5 - Compressive Stress-Strain Curve and Plots of the Ratios of Tangent and Secant Moduli to Young's Modulus as a Function of Compressive Stress for 721-Titanium

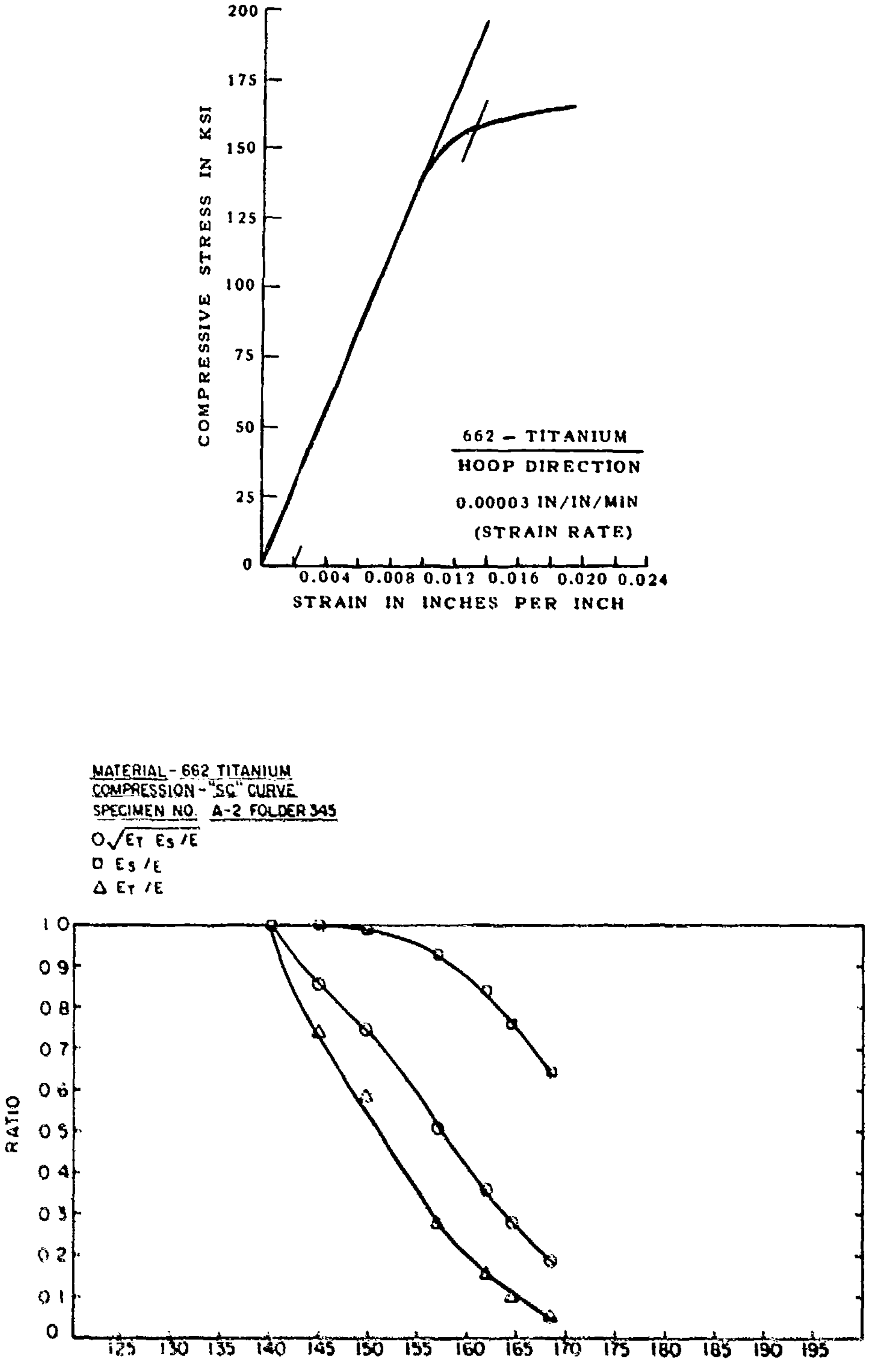

Figure 6 - Compressive Stress-Strain Curve and Plots of the Ratios of Tangent and Secant Moduli to Young's Modulus as a Function of Compressive Stress for 662-Titanium

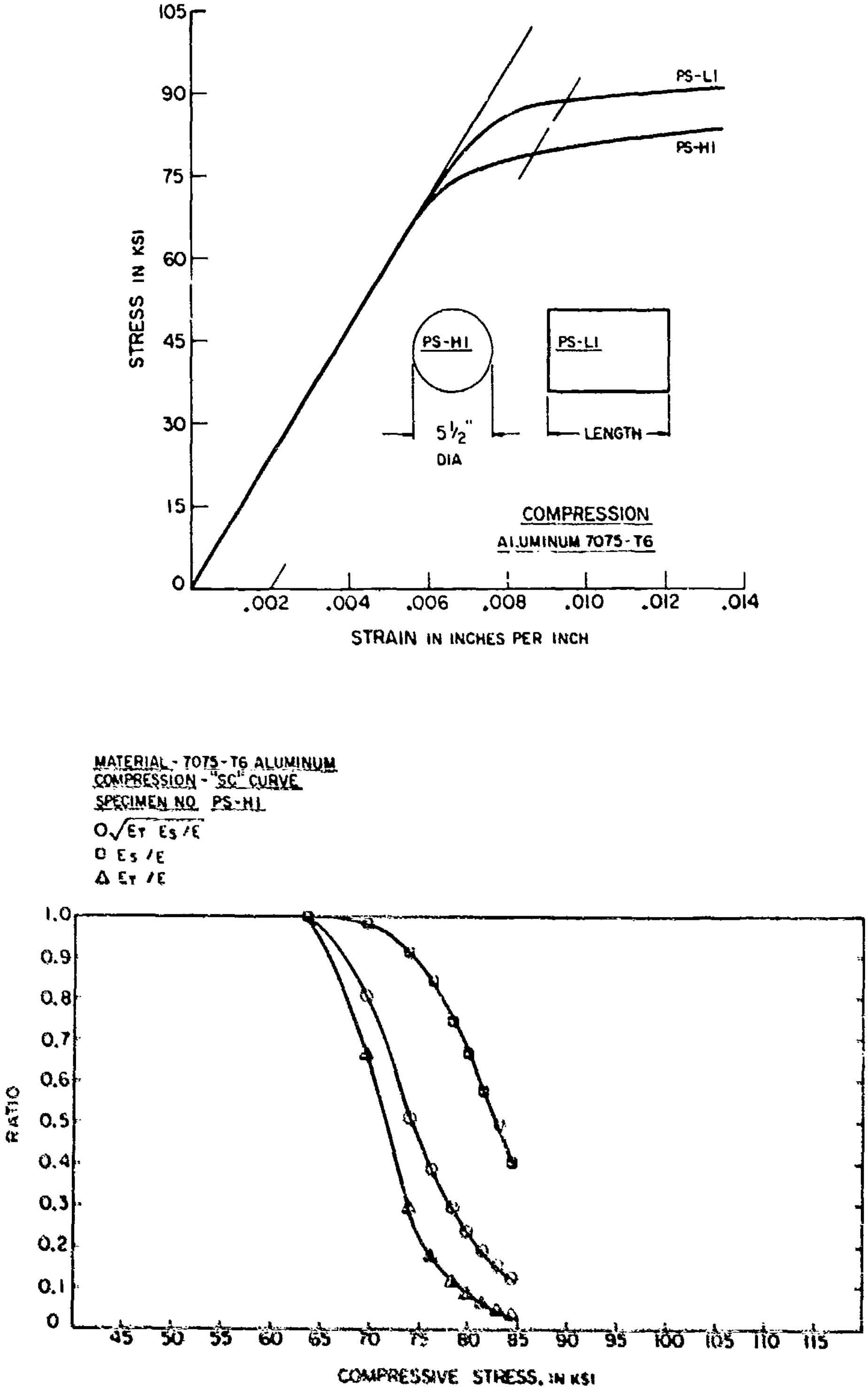

Figure 7 - Compressive Stress-Strain Curve and Plots of the Ratios of Tangent and Secant Moduli to Young's Modulus as a Function of Compressive Stress for 7075-T6 Aluminum

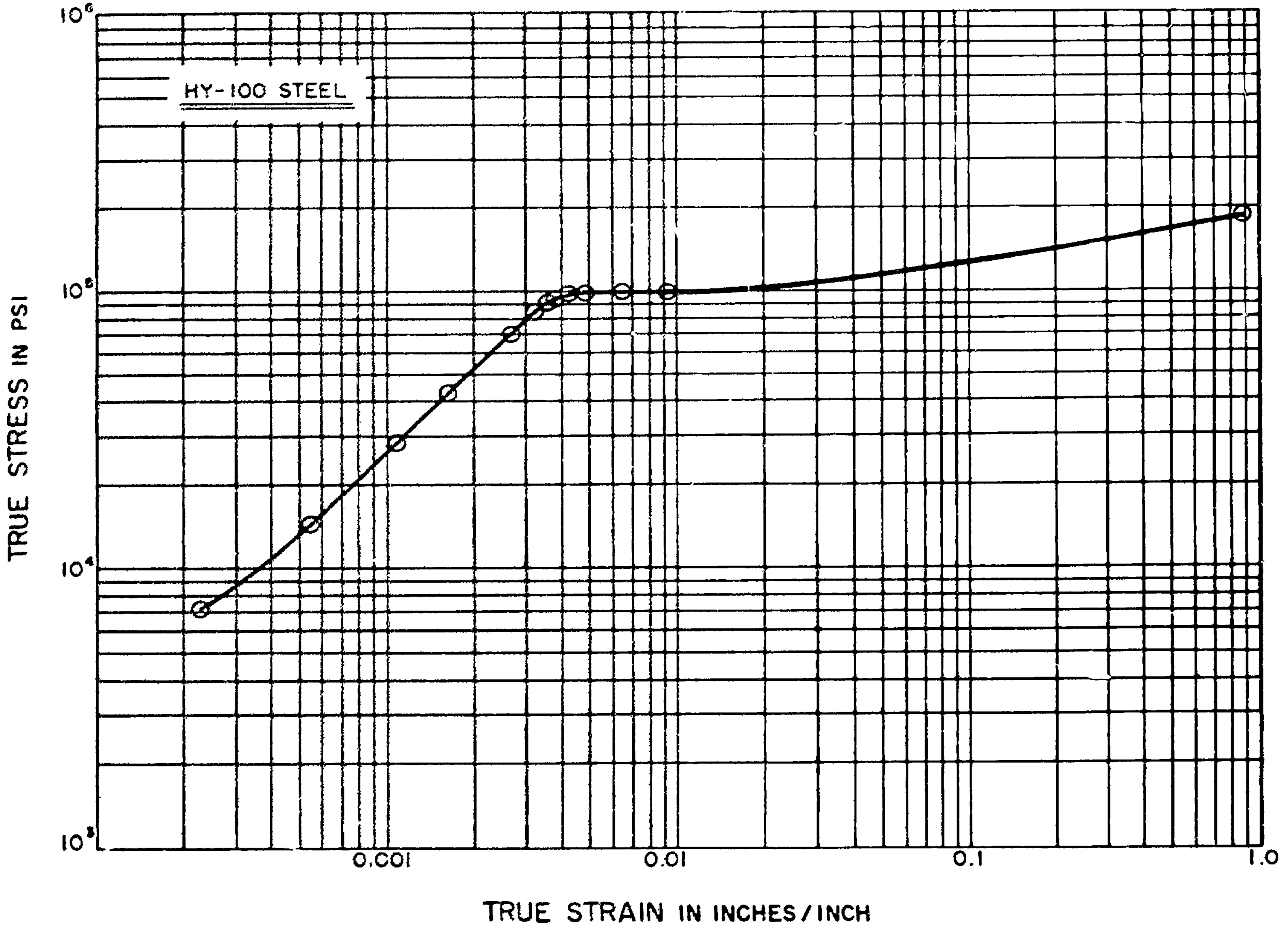

Figure 8 - True Stress-True Strain Tensile Curve for HY-100 Steel

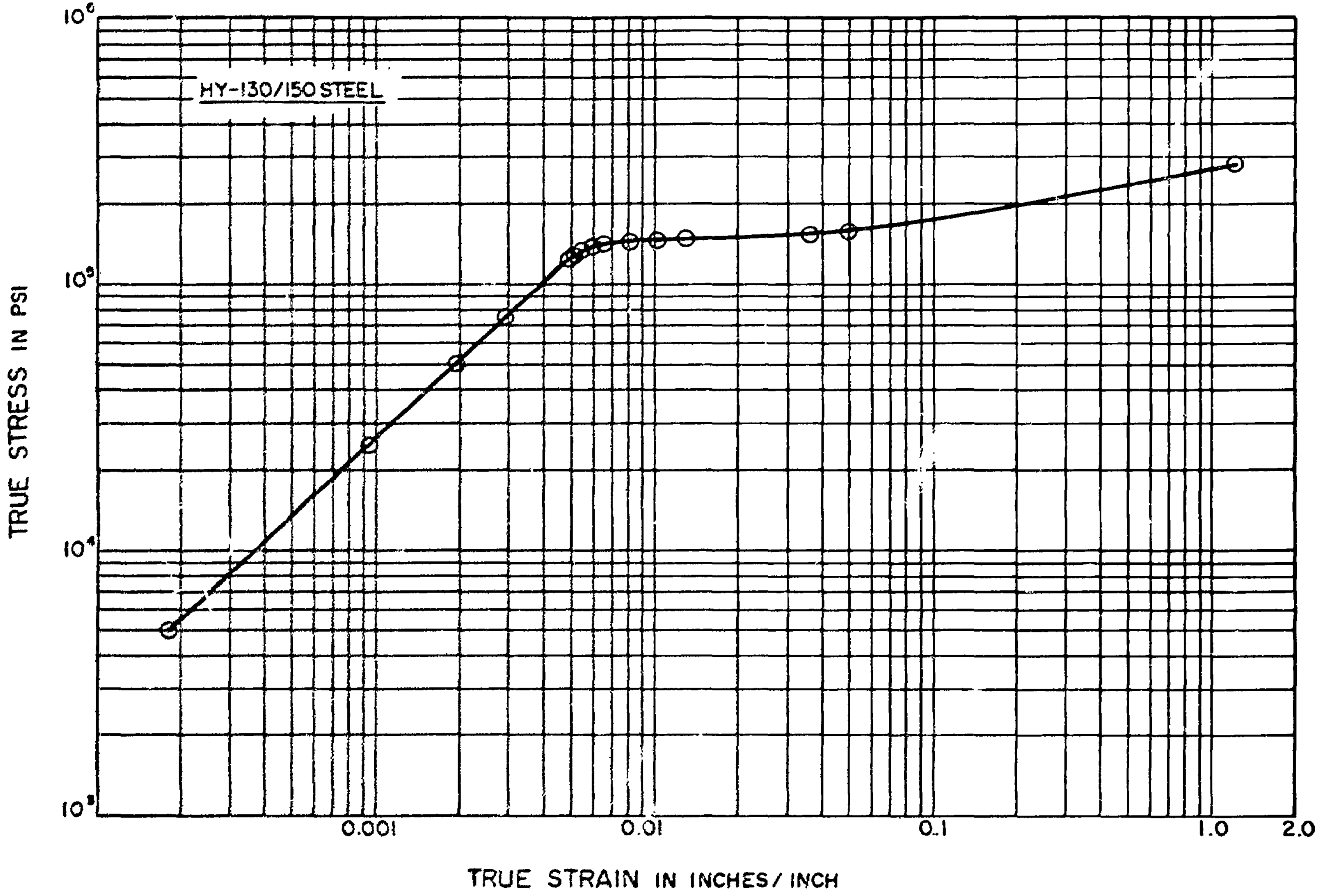

Figure 9 - True Stress-True Strain Tensile Curve for HY-130/150 Steel

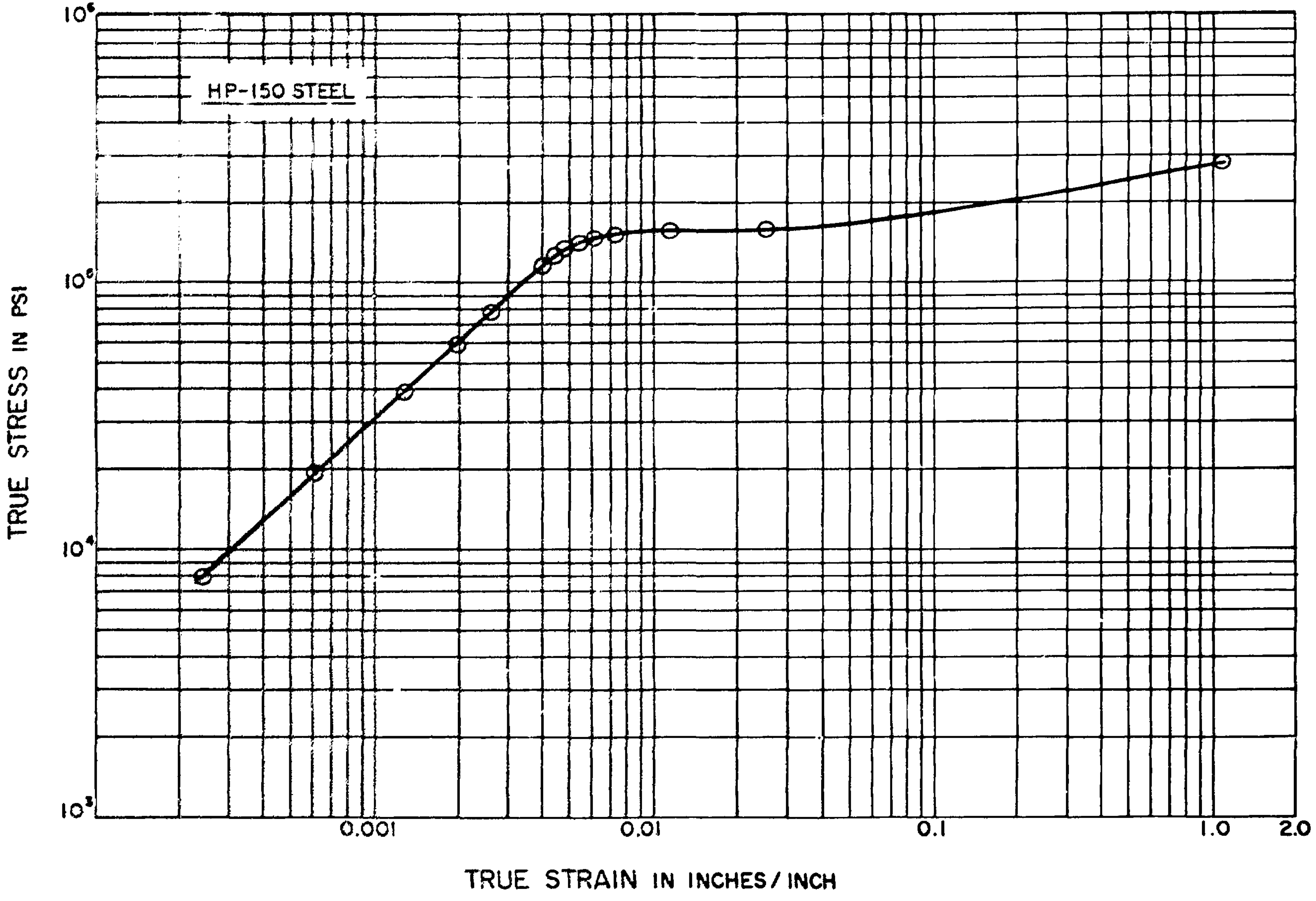

Figure 10 - True Stress-True Strain Tensile Curve for HP-150 Steel

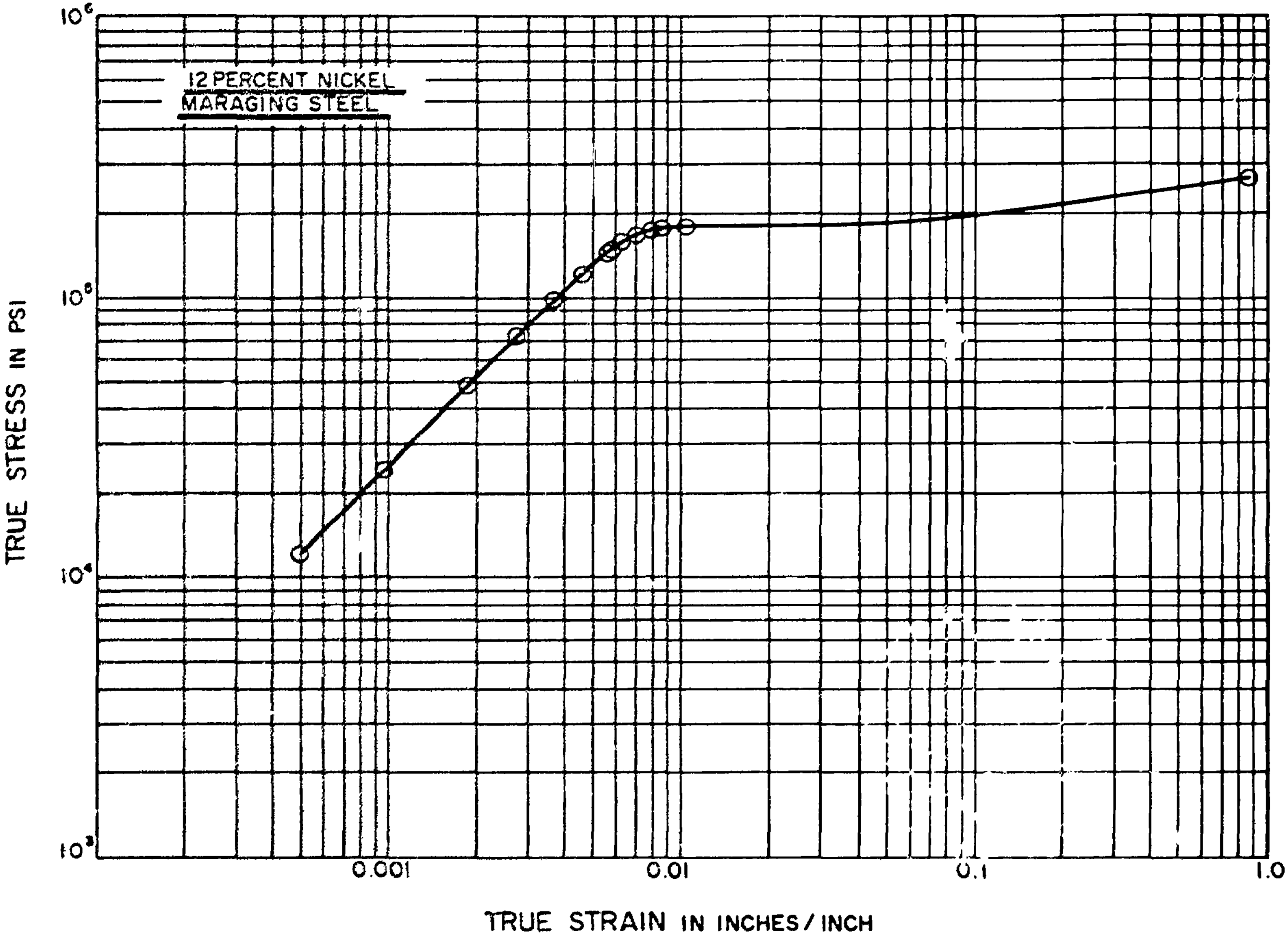

Figure 11 - True Stress-True Strain Tensile Curve for 12 Percent Nickel Maraging Steel

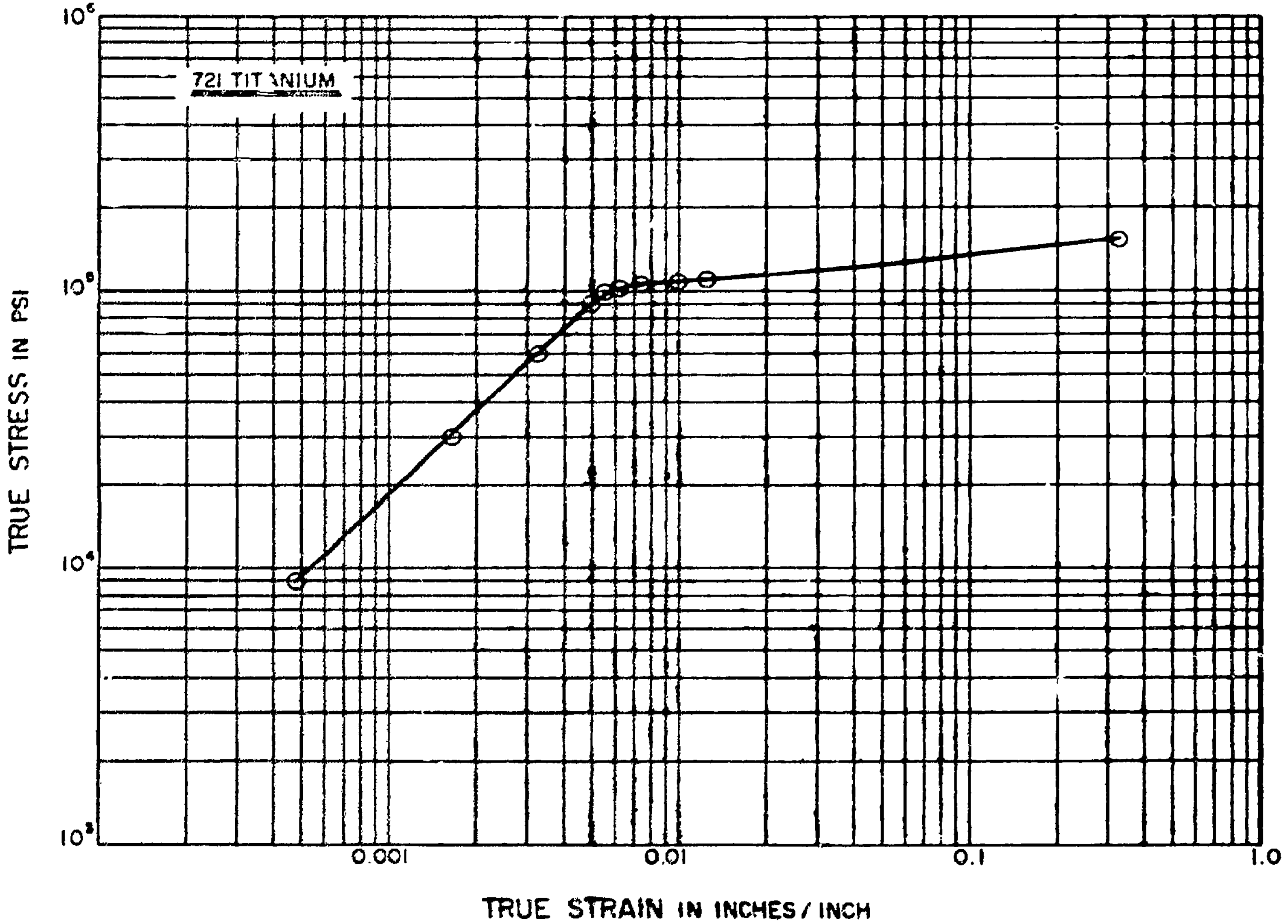

Figure 12 - True Stress-True Strain Tensile Curve for 721-Titanium

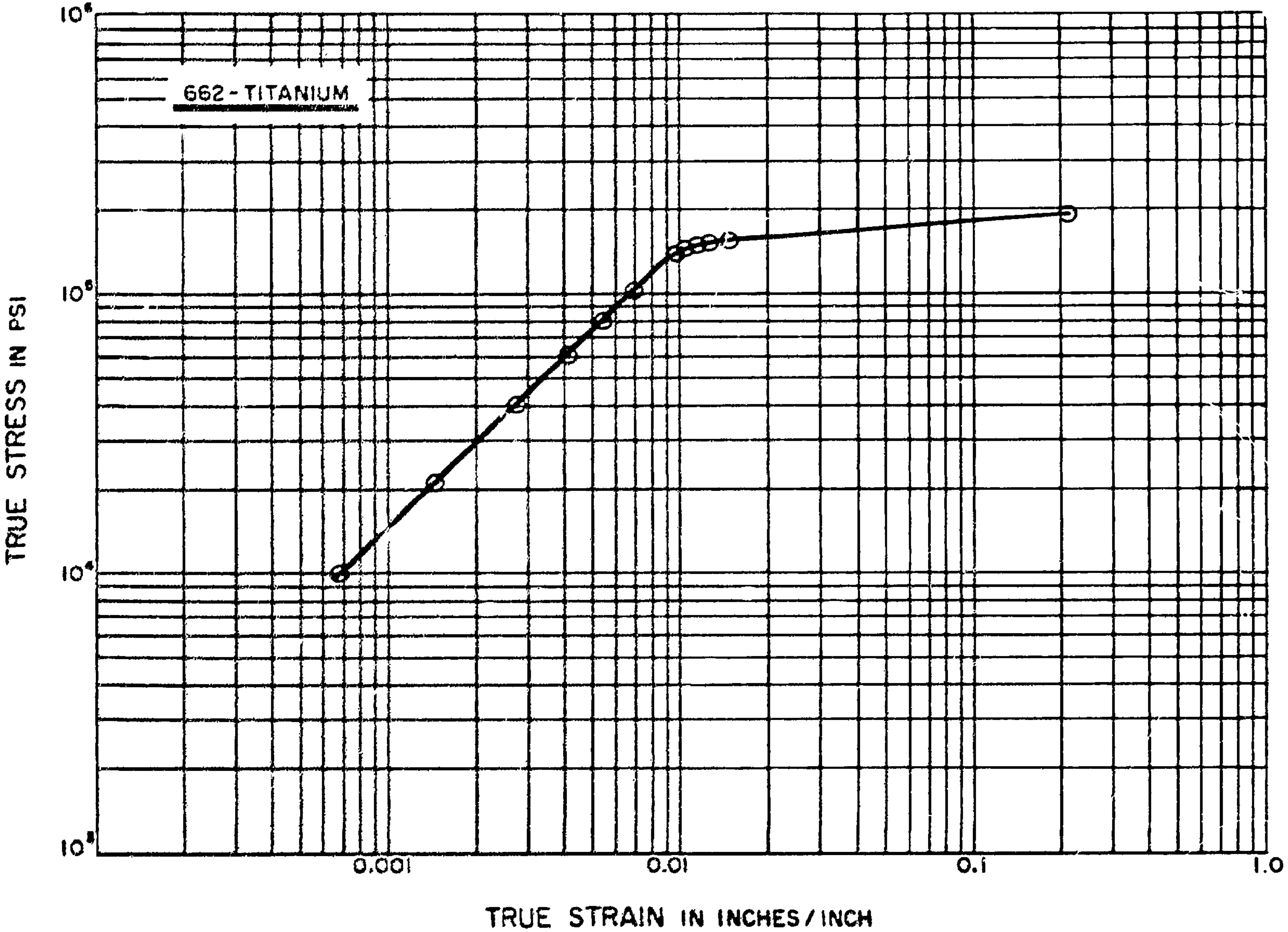

Figure 13 - True Stress-True Strain Tensile Curve for 662-Titanium

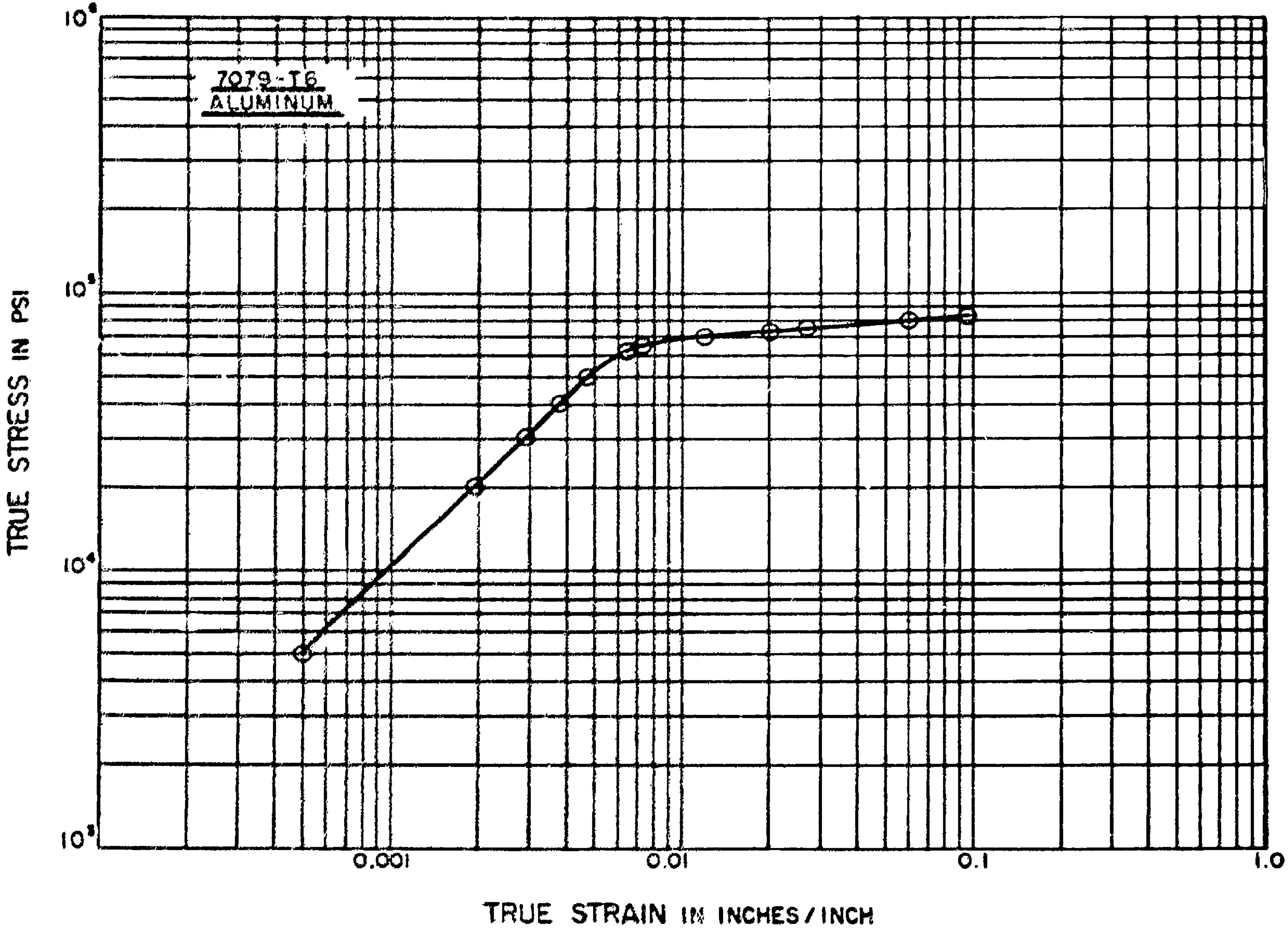

Figure 14 - True Stress-True Strain Tensile Curve for 7079-T6 Aluminum

indicative of strain hardening, show that the titanium alloys have the least tendency to strain harden. True stress-true strain curves are used for evaluating the true-strain behavior of a material under a given loading condition; they also help to determine the ability of a material to deform under high yielding conditions. In other words, in comparing materials, a relative index of the plastic behavior of the material can be obtained by comparing the ratio of the applied true strain to the total true strain that the material is capable of sustaining; the larger the ratio for a given applied strain, the lower the reserve ductility. This concept is important in evaluating low-cycle fatigue life.

FATIGUE

The Marine Engineering Laboratory (MEL) has been evaluating the low-cycle fatigue life of most of the promising materials using alternating bend tests.[5-13] Naval Applied Science Laboratory (NASL) has been evaluating full thickness plate specimens by cyclic pressurization of one plate surface.[14,15] In developing the base material properties of high strength steels for the Navy, U.S. Steel Corporation is using fatigue specimens similar to the MEL alternating bend specimens.[16-20]

The MEL low-cycle corrosion fatigue test results indicate that the aluminums, titaniums and some of the steels will more than meet a suggested criterion of 5000 cycles when loaded to 80 percent of the yield strength. U.S. Steel data show that HY-130/150 steel plate will also meet this corrosion fatigue criterion.

Published and unpublished data are insufficient to indicate whether 12 percent nickel maraging 180,000-psi yield strength steel has an acceptable corrosion fatigue life. However, rotating beam data for this material indicates that maraging steel specimens will have a marginal corrosion fatigue life.[20]

There are no corrosion-fatigue data on weldments of HY-130/150 steel or 12 percent nickel maraging steel. It is expected that the HY-130/150 corrosion fatigue tested weldments will meet the corrosion fatigue criterion of 5000 cycles at 80 percent of yield. On the basis of the information available to date, however, it is not expected that the 12 percent nickel weldments will have the required corrosion fatigue life.

The MEL unpublished data indicate that the corrosion fatigue life of the lower strength aluminums, such as 5456, more than meets the alternating beam requirements set forth above.

Only limited fatigue data are available on the aluminum-columbium-tantalum-titanium alloy systems; the data that have been published[21] indicate that titanium alloys will meet the specimen test criterion. Recent unpublished fatigue studies by MEL show that the 721-titanium alloy has an alternating bend fatigue life in air of over 10,000 cycles when tested at 87 percent of its yield strength. NASL studies[15] of welded titanium plates stressed from 0 to tension showed that the fatigue life of 721-titanium was over 10,000 cycles when tested at 80 percent of its yield strength. There appears to be conflicting data as to the low-cycle, highly strained (plastic) notched corrosion fatigue life of 721-titanium alloys. The Naval Research Laboratory (NRL) indicates that the titanium alloy is sensitive to the corrosive environment whereas MEL rotating beam tests on 721-titanium indicate resistance to corrosion fatigue for the aluminum-columbium-tantalum-titanium system.[21] This difference in fatigue results is attributed to the processing of the two lots of material. The material received by NRL was from the first group of heats to be made of the 721-titanium alloy. NASL has recently performed a 0-to-tension fatigue test on a plate of titanium which catastrophically failed when water was placed on the surface of the plate after 2000 cycles; again the heat of titanium investigated was from one of the first heats to be produced. MEL is presently generating notched corrosion fatigue test data from heats made using both the old and the new processing techniques.

It should be understood that specimen fatigue data are not representative of the behavior of the material in any given structural application; specimen fatigue data are used only as a relative index for discriminating between the behavior of two or more materials. In order to evaluate a material for a structural application, a model of sufficient size should be made to evaluate the actual corrosion fatigue behavior of the material; this study has been undertaken by the Model Basin.

In evaluating the fatigue performance of a material, crack initiation does not necessarily signify fatigue failure; that is, a crack may occur in a localized area where bending gives rise to a localized outer fiber tensile stress. A crack at this point will propagate along the length of the outer fiber until reaching a zone of compressive stresses. The depth to which the crack will propagate through the thickness will depend on the toughness of the material, its resistance to corrosion fatigue, distribution of load over the specimen, and the distribution of stress through the thickness.

Since the weldments to be used in DSSP vehicle design will be equivalent in quality to the weldments used in smooth corrosion fatigue tests and since where localized bending may occur the tensile strains are expected to be below the yield strength of the material, it can be expected that structural weldments made from 721-titanium will be suitable for DSSP applications.

Low-cycle corrosion fatigue data on high strength titanium alloys, 150,000- to 180,000-psi yield strength, have not yet been obtained by MEL. MEL has performed a few welded-box fatigue tests on low strength 6Al-4V-Ti alloy which failed after relatively few cycles. Rotating beam fatigue tests[5] on some of the higher strength alloys indicate that the presently available high strength titanium alloys may not meet the suggested alternating fatigue criterion of 5000 cycles at 80 percent of the yield strength.

Recent MEL test results from welded-box fatigue studies showed that the HY-180 maraging steels failed catastrophically after 1200 cycles when stressed at 53 percent of the yield stress and that the HY-130/150 steel stressed at 80 percent of yield stress fatigue cracked after 2500 cycles.

NOTCH TOUGHNESS

At present, the selection of a notch toughness criterion for the pressure hull material cannot be based upon any fracture mechanics criteria for critical crack length. The material will have to be sufficiently resistant to initiation of crack propagation. It is assumed that in any fabricated structure having the shell thicknesses required for the research and search vehicles, there will be incipient or finite cracks that would grow under certain loading conditions. Therefore, it is necessary to use a notch toughness criterion which will ensure resistance to fracture regardless of mode, catastrophic or shear. To ensure that the material selected will have suitable notch toughness, the material should be able to resist crack propagation in the presence of a 2-in.-long, through-the-thickness crack in a 1-in.-thick plate that has been plastically deformed to a permanent strain of 3 to 5 percent.[22-26] The NRL explosion tear test, used for evaluating the resistance of various alloys to shear failure, indicates that the low strength aluminum alloys, the 721-titanium alloy, the HY-130/150 steel, and the 12 percent nickel, and maraging steels will meet this criterion.

To date, little work has been performed on the explosion tear resistance of welded plates; however, a 1-in. 721-titanium weldment of a plate received from Chance-Vought for evaluating this alloy as a possible hydrofoil material had a drop weight tear energy of approximately 3000 ft-lb in both the weld deposit and the baseplate. Correlation of the drop weight tear test (DWTT) to the explosion tear test (ETT) indicates that the welded 721-titanium alloy can withstand a permanent deformation of from 3 to 7 percent. No data are available on the tear resistance of aluminum or of HY-130/150 steel weldments. It should be understood that the explosion tear test will not have to be performed as a specification requirement, but Charpy V-notch or DWTT tests will have to be performed. These values can be compared with NRL correlation studies.[22-26]

NASL explosion bulge testing of HY-130/150 and HP-150 steels[27] showed that these steel alloys can withstand a reduction in thickness of 3 to 6 percent. Failure initiated in the weldment due to the lower strength of the weld deposit.

No ETT data are available for 12 percent nickel maraging steel weldments; however they are presently being evaluated at NRL. It is assumed that weldments of maraging steels in the 165,000 to 175,000-psi yield strength range will meet the basic toughness requirements.

Objection may be made to the 3 to 5 percent permanent deformation criterion for resistance to propagation of a 2-in.-long, through-the-thickness crack. If a sphere is indented to where a deformation of 3 to 5 percent is obtained, buckling will probably occur before the operating depth is reached. Since the effects of corrosive pitting and pinpoint impacting are unpredictable, it is necessary to select a material with sufficient notch toughness to resist any type of fracture. The plastic deformation criterion may be decreased or it may be increased depending upon model or full-scale studies, but, from all indications, using 3 to 5 percent permanent deformation as a criterion will provide a sound material for a safe vehicle.

CORROSION

General Corrosion

Over the years, a number of reports have been written on the pit degradation of low strength aluminum alloys. The depth of pitting for these alloys depends on the environment. It has been reported that after a 2-year immersion in sea water, the maximum depth of pit for 6061-T4 was 0.021 in.[31] If the depth of pitting is expressed as a linear function of time, the depth of pitting after 10 years would be 0.10 in. Other data show that 6061-T6 can pit from 0.003 to 0.042 in. per year depending upon its sea water environment.[32] Since this pitting takes place on unpainted surfaces, anodizing and plastically impregnating the anodized surface or painting could reduce this pitting to a minimum; however, constant care will have to be taken to maintain the selected coating. Where pitting does take place, it has been shown that the tensile strength of 6061-T6 is reduced with increasing pit depth.[31,33,34]

MEL unpublished data indicate that the corrosion degradation of the 6061-T6 aluminum alloy weldments is similar to that of the base material; however, welded specimens having incomplete fusion between the weld metal and the base material showed rapid deterioration.

The aluminum producers report that the new experimental alloys, such as X7005,[35] X7006,[36] X7106,[37] and X7039,[38] approach the corrosion resistance of 6061-T6 alloy. These alloys, however, are very anodic to other structural materials and precautions must be taken to avoid galvanic corrosion. It should be remembered that these high strength alloys are susceptible to stress corrosion.

U.S. Steel, in evaluating the corrosion resistance of HY-130/150 steel, found for the limited number of tests performed to date that the base material and weldments of the HY-130/150 steels (5Ni-Cr-Mo-V) appear to have better corrosion resistance than the HY-80 steel weldments.[39] U.S. Steel is presently studying the electrochemical behavior of 12 percent nickel maraging steel. To date, they have reported no data.

Titanium alloys are known to be resistant to corrosion degradation in sea water. MEL corrosion specimens which have been exposed to sea water for over 1 year still appear to be in the original condition. From a galvanic corrosion point of view, titanium appears to be superior to all the other materials since it requires no painting, coatings, or sacrificial anodes to protect it.

Stress Corrosion

Stress corrosion does not appear to be a problem for the 5000 series of aluminum alloys in the unaged condition.[28] From all indications, the 6061-T6 alloy does not show any susceptibility to stress corrosion. Unpublished data on the high strength aluminum alloys indicate a greater susceptibility to stress corrosion than was originally predicted. However, the unweldable 7075 alloy when given a proprietary treatment does not show any susceptibility to stress corrosion, but in thicker plates, the yield strength is lowered to around 40,000 psi. Modification of the older and development of new aluminum alloys are being investigated; these alloys show promise of being resistant to stress corrosion.[11]

Tests are presently underway for HY-130/150 steel, and to date no data have been generated by either U.S. Steel or MEL on the stress corrosion characteristics of this steel. The producer of HP-150 reports that this steel is insensitive to stress corrosion by the normal bent beam test.

Eighteen percent nickel maraging steels, which were cyclic loaded to produce a fatigue crack and then stressed to 80 percent of yield strength, indicate a susceptibility to stress corrosion.[29] U.S. Steel reports[30] that stress corrosion was observed in the 12Ni-5Cr-3Mo HY-180/210 maraging steel weldments when exposed in three different sea water environments for 6 to 17 days; they state, however, that the unwelded plate is resistant to stress corrosion cracking and that they expect to establish cathodic protection of the weldment using carbon steel as the sacrificial anode.

NRL is in the process of developing a notched cantilevered beam, stress corrosion test.[31] In evaluating the testing procedures, they noted that the titanium alloys were susceptible to stress corrosion when a fatigue crack was propagated to approximately 50 percent of the depth of the specimen. The titanium alloy plates tested by NRL, however, were made by sheet mill processing procedures and not by those procedures that were being established for producing titanium plates.

In a limited evaluation of the stress corrosion characteristics of 721-titanium alloy using the notched simple beam test, the Model Basin found that low silicon, low manganese, fine-grained 721-titanium alloy was insensitive to stress corrosion when the outer surface is loaded to a nominal stress equivalent to the tensile yield strength or higher. These test results were duplicated on specimens fatigue-notched to a depth between 10 and 50 percent of the thickness of the specimen. Further data on the stress corrosion susceptibility of titanium will be required to verify the results of the limited tests to date.

High strength maraging steels and high strength aluminum alloys show the same susceptibility to notch stress corrosion. The susceptibility of fatigue notched HY-130/150 steels to stress corrosion has not been evaluated to date.

PRODUCTION CONSIDERATIONS

MILL PRODUCTION CAPACITY

In considering manufacture of the pressure hulls of the rescue and search vehicles, it is advantageous to have the minimum possible number of weld joints. Therefore, if spheres, cylinders, or a combination of them are to be considered, the mill production capacity for producing hemispheres using plates, forgings, and spinning or pressing will have to be taken into consideration. The presently available capacity for producing aluminum, steel, and titanium in the required shapes is discussed below and is summarized in Table 3. It should be noted that where spheres are concerned, an additional 1 in. has to be added to the forming blank thickness to permit machine finishing the spheres to the required concentricity tolerance of ± 1/16 in.

The aluminum industry can produce plates weighing up to 17,000 lb. HY-130/150 steel plates can be made up to 30,000 lb in weight, and the HP-150 steel plates can be made up to 17,000 lb. Maraging steel plates up to 30,000 lb can be rolled to 3 in. thick; thicker plates will have to be

TABLE 3

Forming Blank Size and Available Capacity for Materials Considered for DSSP Vehicles

Material	Grade	Search Vehicle			Rescue Vehicle			Rescue Vehicle		
		Diameter Blank Size Required in.	Weight of Blank lb	Available Capacity lb	6-Foot Diameter Blank Size Required in.	Weight of Blank lb	Available Capacity lb	7-Foot Diameter Blank Size Required in.	Weight of Blank lb	Available Capacity lb
Steel	HY-100	—	—	—	2 1/4 x 151	12,100	30,000	2 1/4 x 130	8,959	30,000
↓	HY-140	—	—	—	2 1/2 x 151	13,450	30,000	2 1/2 x 130	9,955	30,000
	HY-150	3 1/2 x 130	14,000	17,000	2 1/4 x 151	12,100	17,000	2 1/4 x 130	8,959	17,000
	HY-160	—	—	—	2 1/8 x 151	11,420	17,000	2 1/8 x 130	8,462	17,000
	HY-180	3 1/4 x 130	13,000	17,000	2 1/8 x 151	11,420	17,000	2 1/8 x 130	8,462	17,000
Steel	HY-200	3 1/4 x 130	13,000	17,000	—	—	—	—	—	—
Titanium	HY-110	4 1/4 x 130	9,030	8,000	2 1/2 x 151	7,200	8,000	2 1/2 x 130	5,309	5,600/8,000
↓	HY-150	3 3/4 x 130	8,000	6,000	2 1/2 x 151	7,200	8,000	2 1/2 x 130	5,309	5,600/8,000
Titanium	HY-190	3 1/4 x 130	7,000	8,000	—	—	—	—	—	—
Aluminum	HY-35	—	—	—	4 x 151	7,200	17,000	4 x 130	5,309	17,000
Aluminum	HY-60	6 1/2 x 130	8,650	17,000	3 x 151	5,400	17,000	3 x 130	3,982	17,000

forged. The higher strength quenched and tempered steel plates such as the 7210 and the 9-4-25 series can be produced in weights to up to 17,000 lb.

Titanium mill capacity is limited by ingot size. One of the major producers can presently cast an ingot weighing 8000 lb which will yield a plate weighing 5600 lb; another producer can cast ingots weighing 10,500 lb for making plates weighing up to 8000 lb. There is sufficient capacity available to make the plating required for the rescue vehicle. However, the maximum size titanium ingot that is presently cast is 32 in. in diameter. For the search vehicle, a 36-in.-diameter ingot is required before it can be upset and forged into a circular disk to get optimum use of the material. In order to make the search vehicle out of titanium using present production capacity, the titanium industry is investigating not only welding of plates, ingots, or billets to increase their maximum effective weight but also making larger ingots.

There is sufficient capacity to make the pressure hulls of the projected vehicles out of aluminum or steel. However, the capacity is limited for making the rescue vehicle pressure hull out of titanium. To make the search vehicle pressure hull from titanium using existing material capacity will necessitate making the sphere out of three pieces, two spun end caps and a forged or rolled center ring. But the titanium industry expects that within 3 years they will be able to make ingots of sufficient size and weight to make one-piece hemispheres. In fact, one producer states that they presently have sufficient furnace-ingot capacity to meet the requirements for a two-piece spherical hull for either depth. To date, however, this producer has not made ingots weighing over 8000 lb.

FABRICABILITY

Fabricability includes a number of areas such as forging, rolling, machining, and joining. The spheres for the DSSP vehicles will be obtained directly from a steel mill or from a fabricator. No difficulty is foreseen in forging, pressing, or spinning hemispheres to the required dimensions.

Forming

The ease or difficulty of rolling a 7-ft-diameter cylinder depends on the material. The HY-35 aluminum alloy should offer no difficulty in the forming process; however, the newer higher strength aluminum alloys will probably have to be given a proprietary aging treatment to minimize (not eliminate) their susceptibility to stress corrosion. This aging of the lower strength and higher strength aluminum alloys can probably be done after welding.

HY-100,-130/140, and -150 alloy steels should offer no problem in roll forming. U.S. Steel has demonstrated the formability of HY-130/150 steels.[40] Although no large sections of this steel have been rolled, formability experiments indicate that there should be no difficulty. The Model Basin has formed HP-150 steel into cylindrical forms using standard equipment.

U.S. Steel reports that 12 and 18 percent nickel maraging steels in both the aged and the solution-treated condition developed localized deformation bands or ripples on the surface of the test specimen and that they developed flat spots, or nonuniform curvature, at the center of the bend.[41,42] The difficulty may be attributed to the narrowness of their test specimen. The Model Basin has rolled 1-in.-thick plates of 18 percent nickel maraging steel in the solution-treated condition with no difficulty. In addition, the Model Basin has rolled 1/4-in.-thick plates of 12 percent nickel maraging steel in the solution-treated and aged condition to a 5-ft diameter.

NASL has recently cold-rolled a 721-titanium plate (2 x 60 x 144 in.), to a 7-ft diameter.[43] The higher strength titanium alloys (HY-150) will probably have to be hot formed; however, it is foreseeable that room temperature rolling procedures can be developed.

Aluminum alloys can probably be made in various shapes as required for cylindrical stiffeners. Shapes have not been fully developed for the higher strength steels and are being investigated. The 721-titanium alloys have been extruded into T-stiffeners for use in structural models. With some experimental work, it is foreseeable that 721-titanium can be extruded in the desired shapes and dimensions. Because of the time element, stiffeners or shapes for the DSSP vehicles will probably have to be pieced together by welding.

Machining

The aluminum alloys are readily machinable; HY-130/150 steel and HY-110 titanium alloy have machinability similar to that of 316 stainless steel. No difficulty has been expressed about machining maraging steel in the solution-treated condition; however, in the aged condition machining is somewhat of a problem. No definite information is available concerning the machinability of titanium at and above 150,000-psi yield strength.

High strength aluminum, HY-130/150 steel, and HY-110 titanium alloys can be sawed with available equipment. The maraging steels and higher strength titanium alloys, however, require either burning or use of abrasive cutoff wheels.

Joining

The lower strength aluminums are readily weldable; however, their joint efficiency is usually taken as approximately 80 percent. If the HY-35 aluminum alloys are to be considered, the section thickness at the girth of the two hemispheres will have to be increased to compensate for the lower yield strength in the weld deposit. The higher strength aluminum alloys are reported to be weldable but again the joint efficiency is below that of the base material. There is no reported commercial application of these high strength aluminum alloys which have been welded and the joint used as an integral part of the structural bearing member. The Model Basin has welded a few of these alloys and found that their ductility as evaluated by the side bend test is less than 3 percent. Others have reported higher ductilities.

The 5Ni-Cr-Mo-V HY-130/150 steel welded by U.S. Steel has successfully passed explosion bulge and explosion crack starter tests.[41,44] The 5Ni-Cr-Mo-V plates heat treated to 130,000-psi tensile yield strength were tougher than those plates heat treated to 140,000 psi; the plates heat treated to 140-ksi tensile yield strength had a greater amount of shear tearing. The shear tearing in the HY-140 was greater than that obtained from HY-80 tested under the same conditions. Another difficulty is that the weld deposits approach a tensile yield strength of only 130 to 138 ksi. However, the low tensile yield strength of the weld deposit which undermatches the HY-140 base material should be of little concern to the designer of DSSP vehicles since its compressive yield strength will probably be at or above the 140,000-psi minimum. The ultimate tensile strength of the weld deposit closely approaches or even exceeds that of the base material.[44]

The Model Basin has successfully welded models using HP-150 steel with weld deposits having a compressive yield strength at 150,000 psi (Note: the tensile yield strength was over 135,000 psi.) The nil-ductility-transition temperature of the weld deposit was -130 F and its Charpy V-notch energy was 48 ft-lb at 32 F. With another heat of HP-150 filler wire, NASL has obtained tensile yield strengths of 140 ksi and Charpy V-notch values of from 45 to 51 ft-lb at test temperatures of 0 and 80 F, respectively.[45] NASL[46] performed explosion bulge tests on welded 2-in.-thick HP-150 steel plate and concluded that the baseplate and weld deposit had satisfactory toughness; however, NASL advises that the baseplate alloy be modified so that its yield strength is below that of the weld deposit.

The Model Basin and NASL[47] have successfully welded 12 percent nickel maraging steel. NASL has found that the Charpy V-notch energy of the weld deposit is relatively low and that after aging, the yield strength of the weld deposit approximated that of the baseplate. Model Basin circular patch tests showed no cracking in the weld deposit. U.S. Steel reports[48] that a filler metal will be developed to make this material almost as tough as the HY-180/210 base material. For the present, however, joining by bolting rather than by welding should be considered in designing a DDSP vehicle of 12 percent nickel maraging steel.

Out-of-chamber welding of titanium is considered commonplace; several firms have developed this capability. Welded stiffened cylindrical titanium models have been manufactured by these commercial contractors for the Model Basin. NASL is investigating and developing out-of-chamber welding of thick titanium plates.[49] The Model Basin has contracted for the manufacture of a welded fatigue model which will have a shell 2 1/2 in. thick. The Model Basin has found that mechanical and notch-toughness properties of welded 721-titanium plate were equal to or exceeded that of the baseplate. NRL has recently drop-weight tear tested a 721-titanium weldment made by a Navy contractor and found that the energy required to tear the weldment was over 3000 ft-lb. This weldment should be capable of resisting a tear when it is permanently deformed 3 to 5 percent in the presence of a 2-in., through-the-thickness notch in the explosion tear test.

Tolerance

Fabricators have been contacted regarding girth tolerances that can be met when welding two hemispheres together; the replies received indicate that concentricity can be kept within ± 0.04 to ± 0.06 in.

DISCUSSION

From a manufacturing point of view, all of the alloys discussed in the preceding section can be made into structural spheres or cylinders. If the maraging steels are considered, they will have to be bolted or glued together since published and unpublished data indicate that weldments are susceptible to corrosion and corrosion fatigue at low stress levels.

From a structural fabrication aspect, there has been a great deal of experience with forming and welding of 721-titanium alloy.

The HY-130/150 steels have been successfully welded in the laboratory, but the chemical composition of the HY-130/150 welding electrodes or wire have not been finalized.

The lower strength aluminum alloys are readily formed and are weldable, but these aluminums will have to be heat treated after welding to obtain optimum properties.

On the basis of the preceding information, it appears that 721-titanium is one of the more promising materials. However, it should be noted that limited fatigue-notched stress corrosion data indicate a susceptibility to corrosion for certain titanium compositions. A few tests performed on the low manganese, low silicon, fine-grained 721-titanium alloy indicate that it is quite resistant to stress corrosion cracking.

Unfortunately, there are no data on the susceptibility of the HY-130/150 steel alloys to stress corrosion. Maraging steels do show a susceptibility even in the unnotched condition at tensile stress levels below the yield strength. The higher strength aluminum alloys are well known for their susceptibility to stress corrosion, and since time does not permit evaluation of proprietary heat treatment of new alloys for the rescue vehicle, those aluminum alloys should tentatively be disregarded until further technical data are developed.

The significance of stress corrosion initiating in a fatigue-cracked area stressed to the yield strength of the material cannot be readily determined. Uhlig[50] states that if stress corrosion cracking is to occur, there must be tensile stresses at the surface. He notes that these tensile stresses can either be generated by applied loads, by internal stresses, or by a combination of both. Tensile stresses in the neighborhood of the yield strength are generally required to generate stress corrosion cracking, but it can take place at lower stress levels in some aluminum and in some stainless steel alloys.

These pressure hulls will be experiencing compressive stresses. There may even be some localized compressive yielding at operating depth. These yielded areas will result in tensile stresses upon surfacing of the vehicle. Again, there may be areas where bending will occur at operating depth, putting one surface into tension; however, these bending stresses should not approach the tensile yield strength of the material. If these vehicles can be stress relieved after forming and welding, it is even more doubtful that tensile stresses will be reached that approach the yield strength of the material. Therefore, this stress corrosion, or corrosion fatigue failure, may be more of a laboratory problem than of practical concern for these vehicles in either the stress-relieved or unstress-relieved conditions.

CONCLUSIONS

1. Because of the short time available for selecting a material for the pressure hull of the rescue vehicle, it appears that the basis for the choice should be the assurance that the material can be procured and fabricated in the time required and that it will perform satisfactorily in its intended service. On this basis, the choice should be HY-100 steel. If HY-100 steel cannot be accepted for use because of weight restrictions, then HY-130/150 steel should be the second choice. If even further weight reduction is required, 721-titanium should be considered.

2. Although the time available for selecting a material for the pressure hull of the search vehicle is considerably longer than that for the rescue vehicle, it seems doubtful that enough information will be available in time to make, with a sufficient degree of assurance, a selection of some of the higher strength lower weight materials now under development. At the present time, it appears that 721-titanium offers the best chance of meeting the material requirements for the search vehicle.

REFERENCES

1. "Status and Projections of Developments in Hull Structural Materials for Deep Ocean Vehicles and Fixed Bottom Installations," Edited by W. S. Pellini, NRL Report 6167 (4 Nov 1964).

2. Development of HY-130/150 and HY-180/210 Steel, Department of the Navy, Bureau of Ships Contract Nobs - 88540, Project SR007-01-01, Task 853 (U.S. Steel Corp. Progress Reports 1-39 for Project 40.018-001 and Reports 1-3 for Project 40.001 -100).

3. Lane, I. R., "Development of Titanium Alloys for Hulls of Deep-Diving Vehicles," MEL R & D Report 194/64 (31 Aug 1964).

4. Development of Aluminum Based Alloys, Department of the Army, Contract DA-36-034-ORD-3559RD, DA Project No. 593-32-004 (ALCOA Annual and Quarterly Reports from Sep 1961 through Sep 1964).

5. Cavallaro, J. L., "Heat Treatment and Mechanical Properties of Near-Alpha Titanium Alloys," MEL R & D Phase Report 220/64 (21 Sep 1964).

6. MEL letter to Chief, Bureau of Ships (Code 634B), NP/10310(862), Assignment 87-113 of 26 Aug 1964.

7. Shalican, A. J. and Asche, W. H., "Engineering Properties of Experimental Production Heats of Maraging Steels," MEL R & D Report 86 107A (2 Jan 1964).

8. Schwab, R. C., "Low-Cycle Corrosion - Fatigue Properties of HY-100 Steel," MEL R & D Report 86 108B (5 Sep 1963).

9. Gross, M. R., "Low-Cycle Fatigue of Materials for Submarine Construction," NEES R & D Report 91197D (14 Feb 1963).

10. Niederberger, R. B., "Fatigue and Notch Bend Properties of High-Strength Aluminum Alloys," NEES R & D Report 910163C (24 Jul 1962).

11. Gross, M. R., "Engineering Properties of HY-250 Alloy Steel," NEES R & D Report 910192 (31 Aug 1961).

12. Gross, M. R., "Investigation of the Fatigue Properties of Submarine Hull Steels," NEES R & D Report 910178B (31 Mar 1961).

13. Niederberger, R. B., "Fatigue and Notch Bend Properties of High Strength Aluminum Alloys," NAVENGXSTRA Report 910163C (24 Jul 1962).

14. "Fatigue Properties of Tee-Fillet Welds in Ti-721 Alloy Titanium Plates," NASL Project 6377-5, Tech Memo 4 (25 Nov 1964).

15. "Fatigue Properties of Butt Welds in Ti-721 Alloy Titanium Plate," NASL Project 6377-5, Tech Memo 3 (31 Aug 1964).

16. Porter, L. F. et al., "Third Quarterly Progress Report: Development of an HY-130/150 Weldment," U.S. Steel APL Project 40.018-001 (24) (1 Apr 1964).

17. Porter, L. F. et al., "Second Quarterly Progress Report: Development of an HY-130/150 Weldment," U.S. Steel APL Project 40.18-001 (17) (2 Jan 1964).

18. Porter, L. F. et al., "Fifth Progress Report: Development of an HY-130/150 Weldment," U.S. Steel APL Project 40.018-001 (38) (1 Dec 1964).

19. Rolfe, S. T. et al., "Low-Cycle Fatigue of Experimental HY-130/150 and HY-180/210 Steels and Weldments," U.S. Steel APL Project 40.018-001 (37) (1 Dec 1964).

20. Haak, R. P., et al., "Rotating-Beam Fatigue Studies of Experimental HY-130/150 and HY-180/210 Steels," U.S. Steel APL Project 40.018-001 (32) (1 Dec 1964).

21. Rosenstein, A. E., "Mechanical Properties of Titanium Alloys," MEL R & D Report 91203 (2 Aug 1964).

22. Puzak, P. P., et al., "Metallurgical Characteristics of High Strength Structural Materials - First Quarterly Report," NRL Memo Report 1438 (30 Jun 1963).

23. Puzak, P. P., et al., "Metallurgical Characteristics of High Strength Structural Materials - Second Quarterly Report," NRL Memo Report 1461 (Sep 1963).

24. Puzak, P. P., et al., "Metallurgical Characteristics of High Strength Structural Materials - Third Quarterly Report," NRL Report 6086 (Jan 1964).

25. Goode, R. J., et al., "Metallurgical Characteristics of High Strength Structural Materials - Fourth Quarterly Report," NRL Report 6137 (Jun 1964).

26. Crooker, T. W., et al., "Metallurgical Characteristics of High Strength Structural Materials - Fifth Quarterly Report," NRL Report 6196 (Sep 1964).

27. "Investigation of Properties of 130 to 150,000 PSI Yield Strength Steel Weldments Using Experimental Filler Wire (LLRI)," NASL Project 9300-1, Tech Memo 22 (25 Nov 1964).

28. Nuderberger, R. B., et al., "Corrosion and Stress Corrosion of 5000-Series Aluminum Alloys in Marine Environment," MEL Paper Presented at Marine Corrosion Symposium NACE Annual Conference (9-13 Mar 1964).

29. "Third Maraging Steel Project Review," Materials Laboratory, Wright-Patterson Air Force Base, Report RTD-TDR-63-4048 (Nov 1963).

30. Loginow, A. W., "Stress-Corrosion Behavior of 12 Percent Nickel Maraging Steel Weldments," U.S. Steel APL Project 40.001-100 (3) (31 Dec 1964).

31. Simmons, T. J., et al., "Pit Depth Measurements as a Means of Evaluating the Corrosion Resistance of Aluminum Alloys in Sea Water," ASTM STP 196 (1957).

32. Lindberg, R. I., "Aluminum in Marine Environments," Marine News (Sep 1960).

33. Mears, R. B. and Brown, R. H., "Resistance of Aluminum-Base Alloys to Marine Exposures," SNAME (1944).

34. Walton, C. J. and Englehart, E. T., "Performance of Aluminum Alloys in Marine Environments," SNAME.

35. Nuernberger, H. H., "ALCOA Aluminum Alloy X7005," ALCOA Green Letter 198 (1 Nov 1963).

36. Niederberger, H. H., "ALCOA Aluminum Alloy X7005," ALCOA Green Letter 196 (15 Jul 1963).

37. Nuernberger, H. H., "ALCOA Aluminum Alloy X7106," ALCOA Green Letter 201 (1 Oct 1963).

38. "Kaiser Aluminum Alloy 7039," Kaiser Aluminum and Chemical Corporation, Dept of Metallurgical Research (May 1963).

39. Williams, E., "Electrochemical Behavior of Experimental Submarine-Hull Steels in Synthetic Sea Water," U.S. Steel APL Project 40.001-008 (1) (30 Sep 1964).

40. Rolfe, S. T., "Formability of Experimental HY-130/150 Steels," U.S. Steel APL Project 40.018-001 (27) (1 Jul 1964).

41. Porter, L. F., et al., "Development of an HY-130/150 Weldment," U.S. Steel APL Project 40.018-001 (38) (1 Dec 1964).

42. Arnold, K. E. and Rolfe, S. T., "Formability of Experimental Maraging Steels," U.S. Steel APL Project 40.18-002 (7) (30 Sep 1963).

43. Metalworking News, p. 20 (11 Jan 1965).

44. Gross, J. H., "Preliminary Explosion-Bulge Tests of Experimental HY-130/150 Weldments," U.S. Steel APL Project 40.018-001 (23) (1 Apr 1964).

45. "Investigation of Properties of 130 to 150,000 PSI Yield Strength Steel Weldments Using Experimental Filler Wire (LLRI)," NASL Project 9300-1, Tech Memo 22 (25 Nov 1964).

46. "Investigation of the HP-150 Steel-Filler Wire System for High Strength Steel Fabrication," NASL Project 9300-1, Tech Memo 13 (27 Jul 1964).

47. "Investigation of the 12 Percent Nickel Maraging Steel Filler Wire System for High Strength Steel Fabrication," NASL Project 9300-1, Tech Memo 21 (10 Nov 1964).

48. Gross, J. H. "Higher Strength Steel Weldments for Submarine Hulls - Second Status Report," U.S. Steel APL Project 40.018-001 (39) (4 Jan 1965).

49. Nagler, H., et al., "Out-of-Chamber Welding of Ti-7Al-2Cb - 1 Ta Alloy Titanium Plate," NASL Project 6377-4, Progress Report 2 (21 Aug 1964).

50. Uhlig, Herbert H., "The Corrosion Handbook," John Wiley and Sons (1948).

51. Krenzke, M. A., et al., "Potential Hull Structures for Rescue and Search Vehicles of the Deep-Submergence Systems Project," David Taylor Model Basin Report 1985 (Mar 1965).

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13. ABSTRACT

Factors influencing the selection of materials for the pressure hulls of vehicles for the Deep Submergence Systems Project are presented. Aluminum, steels, and titanium are discussed with respect to such properties as chemistry, strength, fatigue, toughness, and corrosion. The suitability of these materials from a fabrication standpoint is also explored. It is concluded that 721-titanium alloy appears to be the best candidate for the pressure hulls of deep-submergence vehicles where high-strength low-weight characteristics are required.

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Deep-Submergence Materials						
High Strength Steels						
Titanium Alloys						
Aluminum Alloys						
Deep Submergence System Project						
Deep submergence vehicles						

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David Taylor Model Basin. Report 1987.
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UNCLASSIFIED

Factors influencing the selection of materials for the pressure hulls of vehicles for the Deep Submergence Systems Project are presented. Aluminum, steels, and titanium are discussed with respect to such properties as chemistry, strength, fatigue, toughness, and corrosion. The suitability of these materials from a fabrication standpoint is also explored. It is concluded that 721-titanium alloy appears to be the best candidate for the pressure hulls of deep-submergence vehicles where high-strength low-weight characteristics are required.

1. Deep sea vehicles—Materials—Development
2. Search vehicle—Materials—Development
3. Titanium alloys
4. Aluminum alloys
5. Steel
6. Pressure hulls—Materials—Strength

I. Willner, A. R.
II. Salive, M. L.
III. Deep submergence systems project

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